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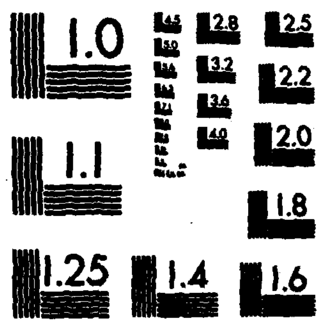

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MEMORANDUM REPORT ARBRL-MR-[illegible]

TANK CAR HEAD SHIELD FATIGUE EVALUATION

Willis F. Jackson
Charles E. Anderson, Jr.

November 1982

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BALLISTIC RESEARCH [illegible]
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An experimental program was performed to evaluate the fatigue damage sensitivity of a railroad tank car head shield, required by Federal Regulation HM-144 in the transport of certain hazardous materials. The test procedures and data collected are documented. Analysis of the data obtained from these tests showed that currently applicable head shield specifications were met.

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I. INTRODUCTION AND BACKGROUND

In recent years, much work has been done under the auspice of the Department of Transportation (DOT) to reduce the dangers associated with the transportation of hazardous materials by railroad tank cars. One important phase of the effort consisted of the development of a shield system to decrease the likelihood of a tank car being punctured by the coupling mechanism of an adjacent car as a consequence of a rail accident.

This work has resulted in the promulgation of amendments to Parts 173 and 179 of Title 49, Code of Federal Regulations, which govern the construction and use of railroad tank cars. One of these regulations (Federal Regulation HM-144) issued by the Materials Transportation Bureau, Department of Transportation, mandates that a tank head puncture resistance system, referred to as a tank car head shield, be affixed to specified rail tank cars. This regulation, issued 15 September 1977 (Federal Register, Volume 43) applies to all DOT classification 112 and 114 tank cars which are used for the shipment of hazardous materials such as liquefied flammable gases and anhydrous ammonia.

The work in this area is being conducted as part of the Federal Railroad Administration (FRA) Tank Car Safety Program. The Ballistic Research Laboratory (BRL), under contract to the FRA/DOT, has been instrumental in the success of the Tank Car Safety Program almost from its inception by fabricating testing facilities, performing experimental tests and conducting theoretical analysis.

Assuming that a tank car head shield has proven to be effective in protecting a tank car from sustaining a puncture due to an accident, an additional requirement is that the head shield and its attachments to the tank car be capable of withstanding the forces and vibrations due to normal railroad operations without losing their designed shielding capabilities. Currently there are AAR test standards which must be met by a candidate head shield to ensure this capability. However, further test procedures are needed to evaluate the head shield and its attachments in terms of long range cumulative fatigue effects.

In previous DOT work, where a specific tank car head shield design was evaluated for its susceptibility to fatigue damage,[1,2] it was determined that the most serious situation during normal operations is the car coupling impact environment (or "humping") and that if the shield can withstand the effects of this environment without significant fatigue damage, then there will be ample margin for safely absorbing the effects from all other over-the-road environments.

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[1] *A. Phillips, "Phase 05 Report on Head Shield Fatigue Tests," (AAR-R197), Railroad Tank Car Safety Research and Test Project, November 1975.*

[2] *R. Johnson, "Selected Topic in Tank Car Safety Research, Vol I: Fatigue Evaluation of Prototype Tank Car Head Shield," FRA/ORD-78-32, I, August 1978*

The approach taken in this study to develop a procedure for determining long range fatigue effects was to perform a series of tank car coupling impact tests with instrumented head shields and to record measurements which reflect the dynamic response of the head shield (and its attachments) and then to devise a method for extrapolating these values in a cumulative way over a long period of time.

The specific test conditions were chosen primarily on the basis of requirements provided in the Association of American Railroads (AAR) document entitled "Specifications of Tank Cars." These requirements set certain criteria which must be met before judging a specific head shield design as acceptable. These criteria, delineated in Appendices A, B, and C, constitute immediate standards of performance which naturally must be satisfied before any consideration of long term fatigue effects can be justified.

All testing performed in the present study was accomplished at Aberdeen Proving Ground, Maryland. The BRL provided and installed the required instrumentation, but the US Army Material Test Directorate (MTD) executed the test program because of their extensive experience in proof testing. MTD provided the required data recording equipment and conducted the tests according to a prescribed test plan. All raw data were transferred to BRL for subsequent reduction and analysis.

II. OBJECTIVES

The primary objective of this program was to examine in detail the fatigue performance of a typical railroad tank car head shield and its attachments when subjected to a car-coupling impact environment. This included performing tests in compliance with the specification set forth by the AAR for evaluating tank car head shields. However, since this was a research effort, further testing was performed using different test configurations so that additional car-coupling impact conditions of interest, meeting the needs of the secondary objective, could be examined.

The secondary objective was twofold. The first part was to evaluate the present test criteria for establishing the structural adequacy of head shield designs and attachments. The second part was to obtain indications of potential modes of head shield structural failure, which might occur after prolonged service, so that attention can be directed toward these areas during routine inspections.

This report deals only with the primary objective even though all the various testing procedures and conditions are described herein. The urgent need for an evaluation of this particular prototype head shield, subject to Federal Regulation HM-144, dictated that this investigation be limited to those data relevant to achieving the primary objective. An analysis of the data and conclusions relative to the secondary objective will be documented in a subsequent report.

III. THE TANK CAR HEAD SHIELD AND TEST INSTRUMENTATION DESCRIPTION

The tank car used in the tests was provided by the Phillips Petroleum Company and the car had the following characteristics:

Owner's No.	PSPC21725
Classification	112A400W
Service	Anhydrous Ammonia
Built	January 1958
Tank Capacity	14,656 gallons (55.48 KL)
Capacity	110,000 pounds (49.4 Mg)
Light Weight	66,400 pounds (30.1 Mg)
Water Capacity	122,059 pounds (55.36 Mg)

The head shield used in the tests was designed, fabricated, and installed by RAILGARD, Inc. Figure 1 shows the head shield in place on the tank car. The head shield stands vertically and is situated so that in the event the car is impacted by a coupler during an accident, the head shield will intercede with the tank, thus minimizing the likelihood of a puncture. Construction details of the head shield are shown in Figure 2. The bottom of the head shield is bolted to two brackets which in turn are welded to the center sill (the main support beam running the length of the tank car). In addition, the head shield is supported by two struts (braces) which are connected to either side of the shield toward the top and also connected to the bolster (a section of the main frame of the car which supports the tank), Figure 3 shows a view of the head shield and how it was attached to the car. Identical head shields were attached to both ends of the car.

A dynamic finite element analysis of the head shield under representative car coupling impact conditions was conducted by Dr. Wilkinson of Louisiana Tech University. The purpose of this analysis was to create a basis for choosing appropriate locations for the instrumentation. Typical results, presented in Figure 4, show that the most likely positions for high stress levels in the head shield were below and inside of the attachment between the side strut and the shield and above and outside of the attachment to the center sill connecting bracket. Consequently, these two areas were instrumented for measuring strains. Other positions were also instrumented to obtain a broader understanding of the response of the shield to dynamic loads.

A summary of the information concerning the strain gauges used in the tests is presented in Table 1. There were five different positions where strain gauges were installed. The number 1 position is located near the point where the strut is attached to the head shield, the number 2 position is located above and to the right of the bracket attachment to the head shield and the center sill, the number 3 position is located near the top and center of the head shield, and the number 4 position is located near the bottom of the head shield and to the right of the bracket connecting the head shield to the center sill. Strain gauges were placed on the front and rear surfaces of the shield at this position and were wired in a two-active-arm bridge configuration sensitive to the bending moment. These

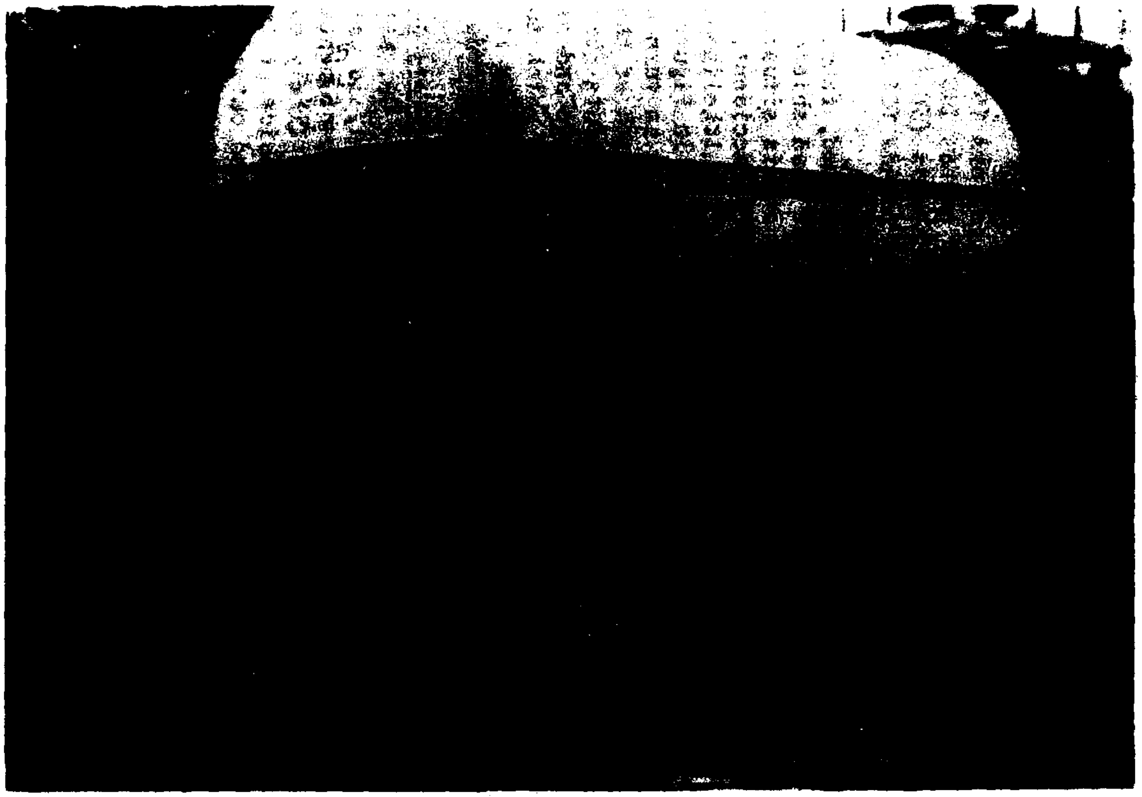


Figure 1. Test Car With Head Shields Installed With Instrumentation.

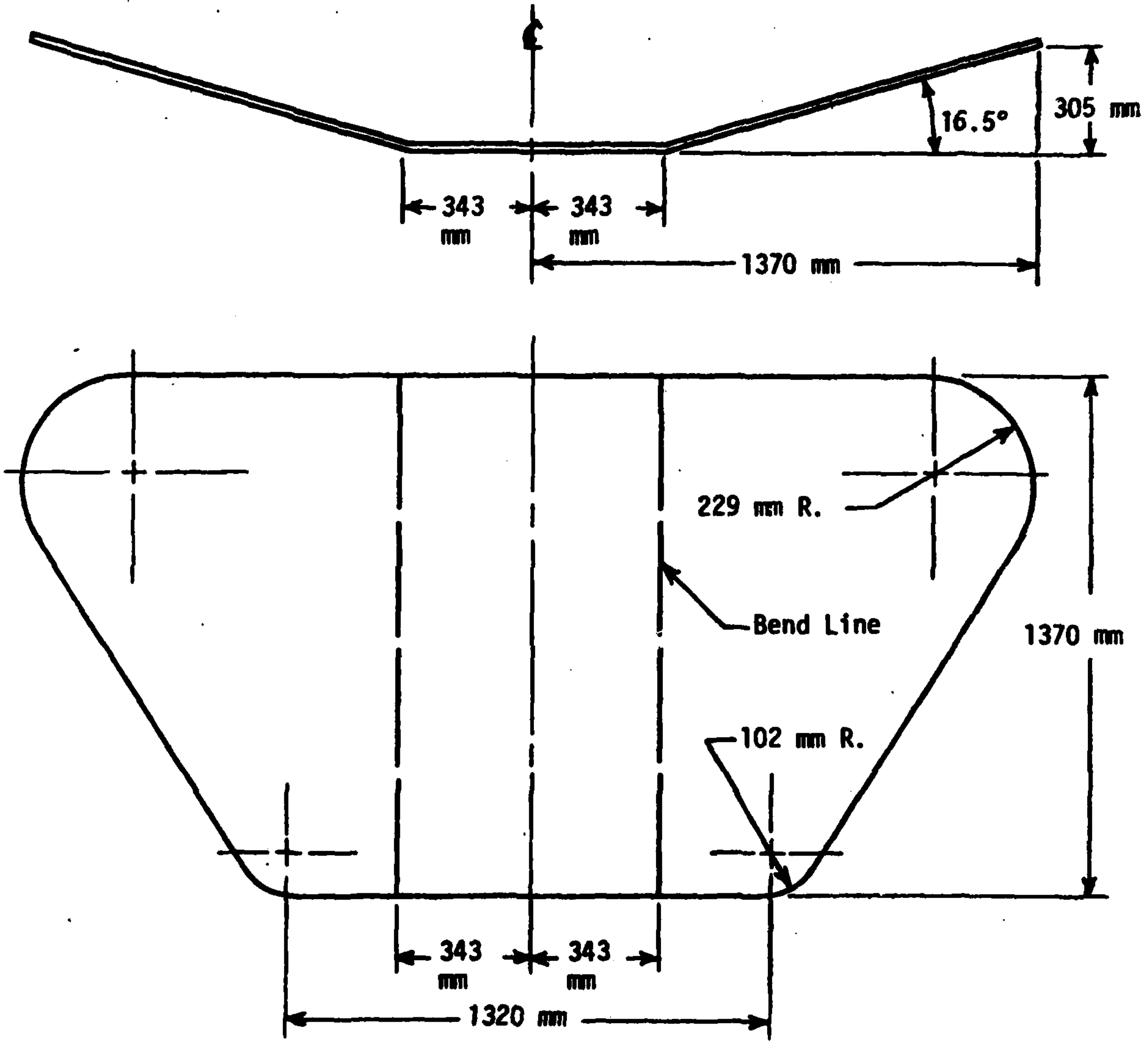


Figure 2. Front View of Head Shield Plate

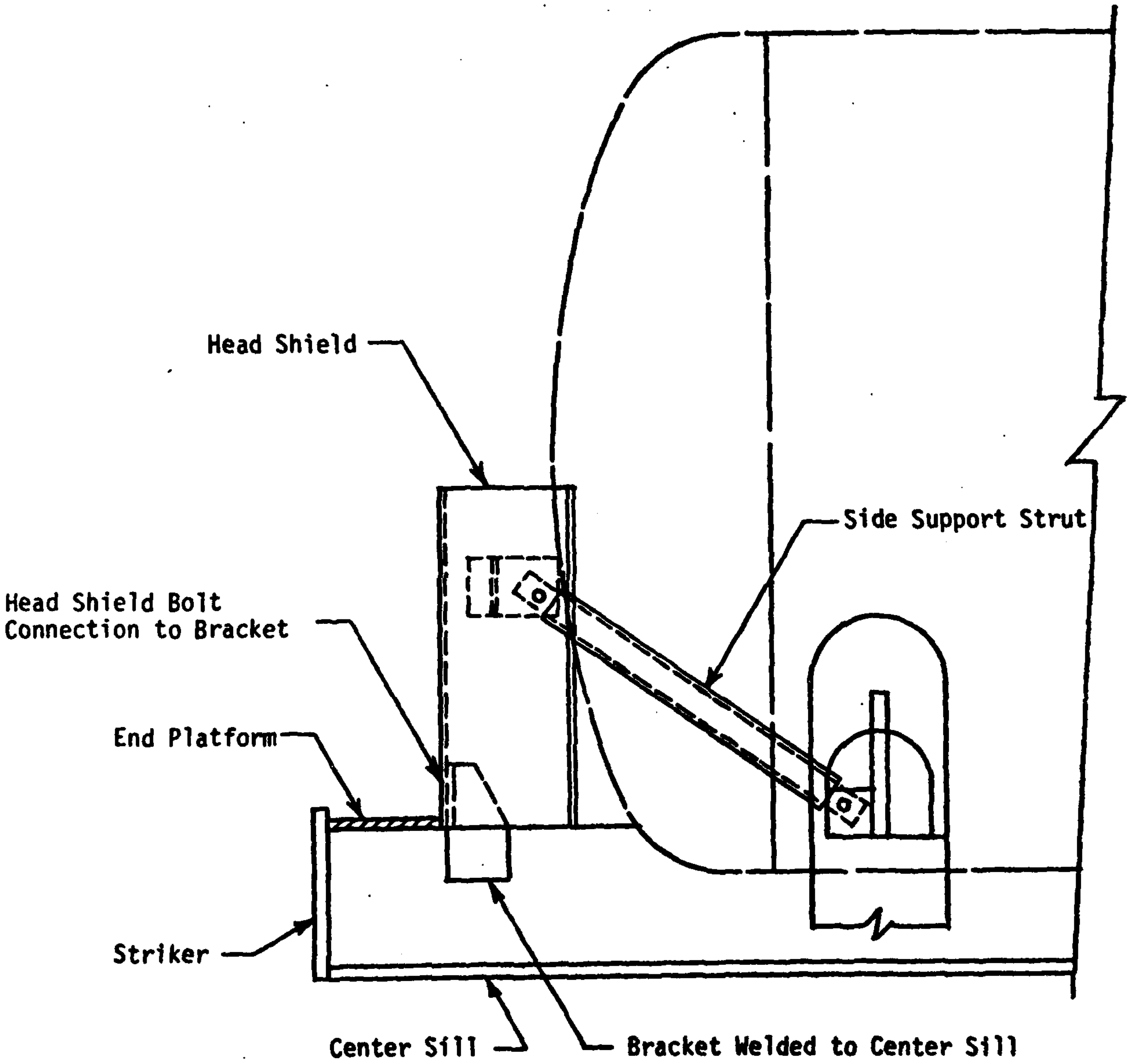
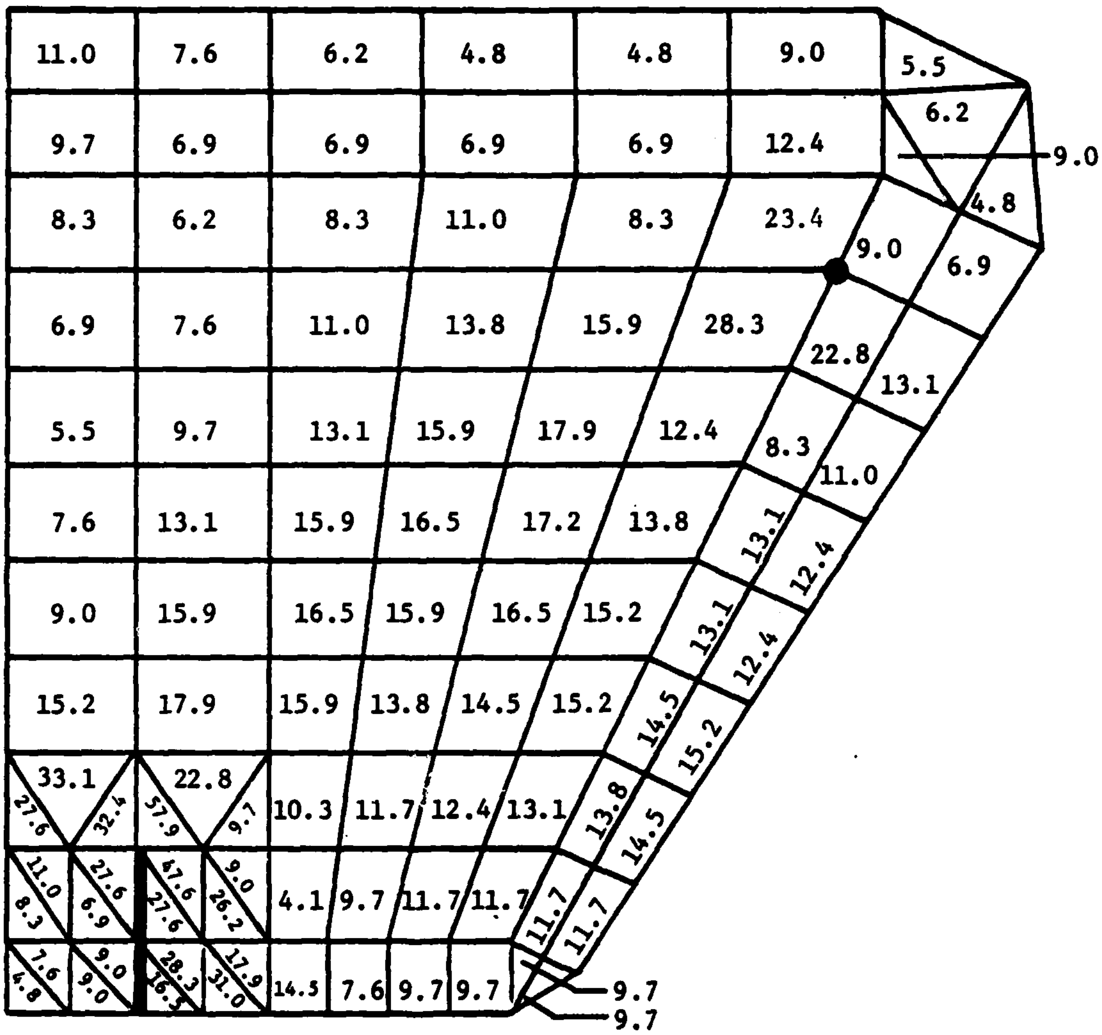


Figure 3. Head Shield Attachment Details



Units: Megapascals

Figure 4. Maximum Predicted Stresses in the Head Shield.

TABLE I. INSTRUMENTATION USED ON TANK CAR HEAD SHIELD TESTS

Gauge Channel No.	Type	Orientation (V: Vertical H: Horizontal S: Slant)	Gauge Position (See Figs 5 and 6)	Location
1	Strain	V		Left
2	Gauge	S	2	Side
3	Rosette	H		Front
4	Strain	V		Left
5	Gauge	S	2	Side
6	Rosette	H		Rear
7	Strain	V		Right
8	Gauge	S	2	Side
9	Rosette	H		Front
10	Strain	V		Right
11	Gauge	S	2	Side
12	Rosette	H		Rear
13	Strain	V		Right
14	Gauge	S	1	Side
15	Rosette	H		Front
16	Strain	V		Right
17	Gauge	S	1	Side
18	Rosette	H		Rear
19	Strain	V		Left
20	Gauge	S	5	Center Sill
21	Rosette	H		Bracket
22	Strain	V		Right
23	Gauge	S	5	Center Sill
24	Rosette	H		Bracket
25	Single Element	Along		Left Strut Support
26	Strain Gauges	Axis		Right Strut Support
27	Single Element	H	3	Front Center
28	Strain	H	4	Left Side*
29	Gauges	H	4	Right Side*
30	Dynamometer	H	-	Instrumented End
31	Couplers (force)	H	-	Noninstrumented End
32		V	-	Instrumented End
33	Accelerometers	H	-	Instrumented End
34		V	-	Noninstrumented End

*Single gauges on front and back side wired into a two-active-arm strain gauge bridge sensitive to bending in the plate.

four positions on the right of the shield are noted in the diagram presented in Figure 5. The number 5 position is located on the bracket connecting the head shield to the center sill, as shown in Figure 6. The strain gauges were placed at these five positions as indicated in Figures 5 and 6. In addition to these locations, single element strain gauges were applied to each of the head shield support struts.

The two conventional couplers on the test car were replaced with calibrated dynamometer couplers for the test series. These provided the measurement of coupler force for each impact.

Three accelerometers were attached to the test car to measure its acceleration response to the impacts. Accelerometers were attached to the center sill at each end of the car and oriented for sensitivity to vertical motion. The third accelerometer was also attached to the center sill at the end of the car supporting the instrumented head shield, but oriented for longitudinal sensitivity. All three accelerometers (CEC Type 4-202) were unbonded strain gauge type having a bridge resistance of 350 ohms.

The gauges were connected to appropriate signal conditioning and recording equipment by means of a bundle of four-conductor shielded cables. The equipment was located in a trackside mobile van. The signal conditioners provided excitation, balance adjustment, and amplification of all transducer signals for recording. The data were recorded using three Sangamo FM tape recorders, operating at a tape speed of 7.5 inches per second. A voice channel and a time code channel were also assigned to each recorder providing time base coherence for all of the data channels.

The recorder channel assignments for the strain gauges are listed in Table 1. Each of the rosette strain gauges required three recording channels corresponding to the three orientations (vertical, slant, and horizontal). The single element strain gauges required one channel each.

Two lever switches actuated by the passage of a wheel were mounted on the track close to the impact point. The car speed at impact was calculated from the time required for the leading wheel to travel to the known distance between the switches.

IV. TEST CONDITIONS AND PROCEDURES

There were three conditions under which the head shield was tested. The first condition (Figure 7) consisted of the test car (the car with the instrumented head shield) acting as a restrained "anvil" car. The test car (filled with water to its load limit) was coupled to a string of three fully loaded flat cars and, after removing all the slack between cars, the brakes on all four cars were set. The test car was impacted by a "hammer" car of 63.5 Mg (70 tons) capacity loaded to its allowable gross weight. The second test condition (Figure 8) was the same as the first except that the test car, which was the "anvil" car, was empty, unrestrained (no back-up cars), and free-to-roll. For the third condition, (Figure 9) the test car acted as the "hammer" car. In this case the test car was accelerated to the required

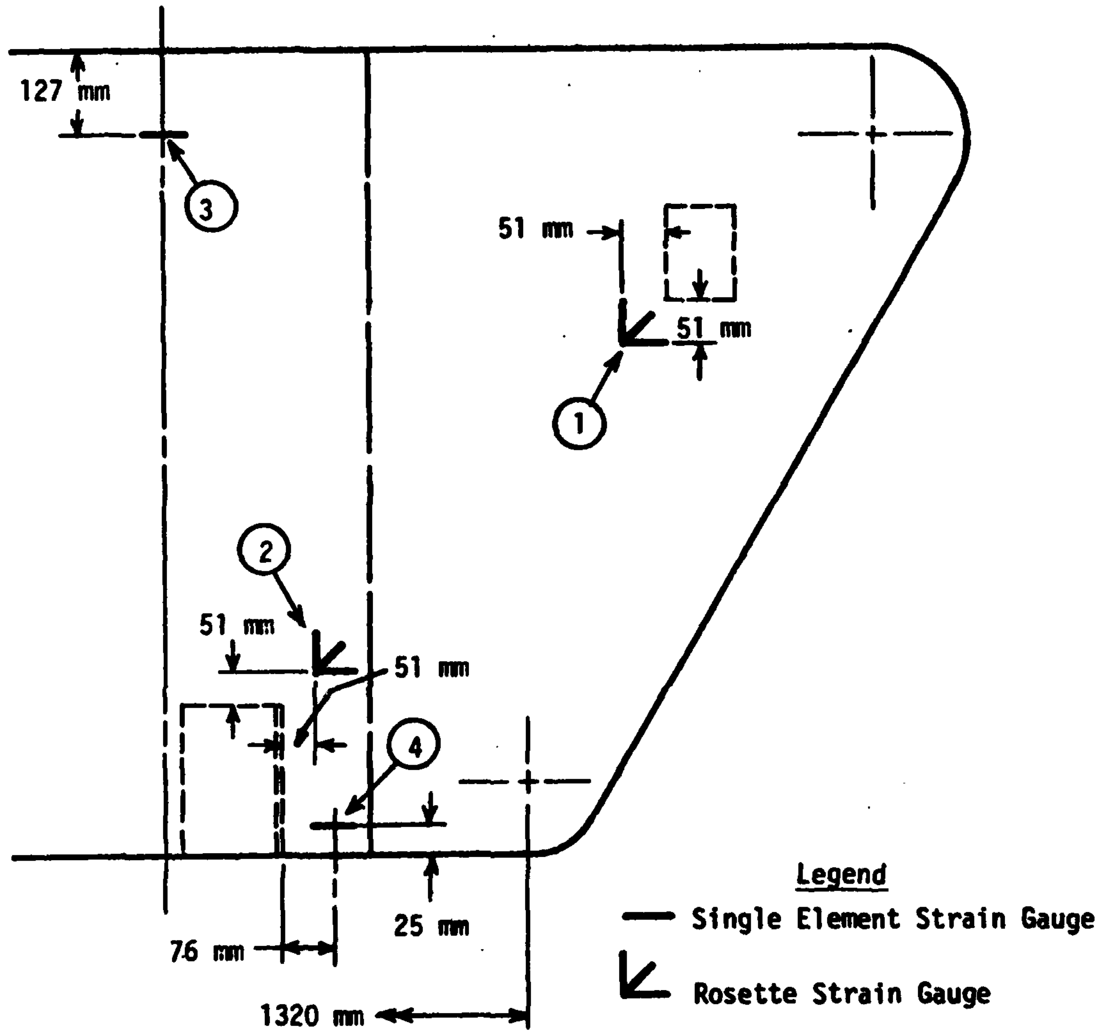


Figure 5. Strain Gauge Positions on Head Shield

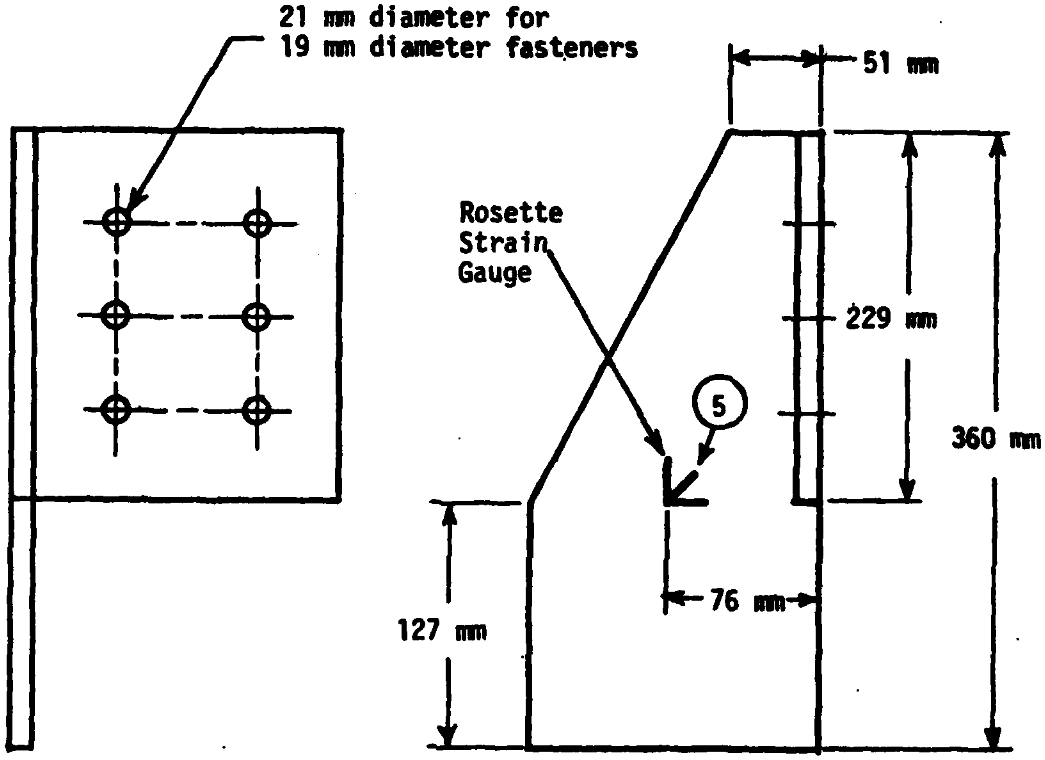


Figure 6. Rosette Strain Gauge Placement on Bracket

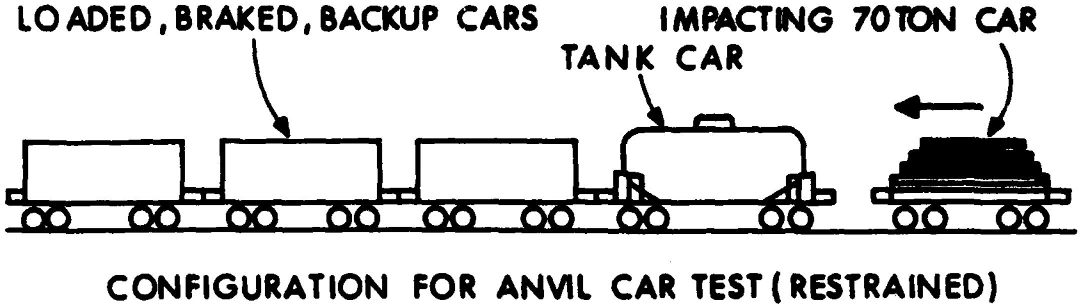


Figure 7.

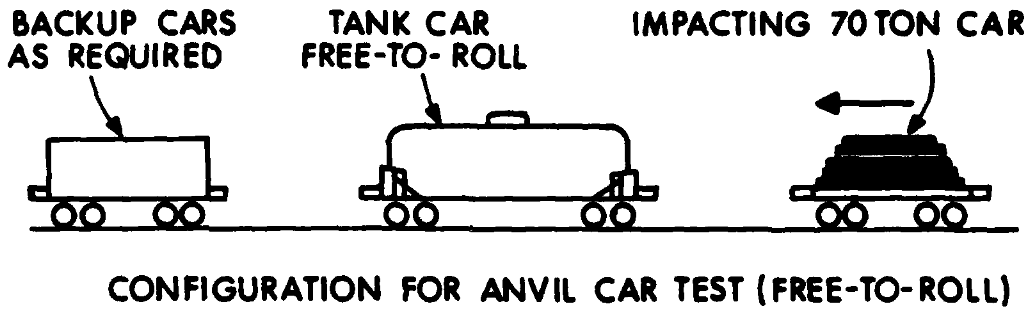


Figure 8.

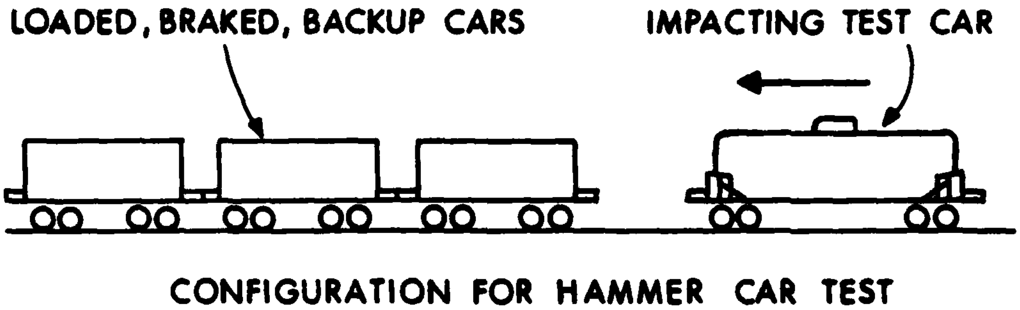


Figure 9.

speed and then impacted into the string of three flat cars described under the first test condition.

The first and second test conditions conform to the requirements delineated in AAR .24-5 (Appendix B) and AAR .25 (Appendix C), respectively. The third test condition was added to the test series because it was felt that it will give severe resisting forces to the impacting tank car and may represent the upper limit to conditions found in normal operating service.

For each of these three test conditions a series of tests were conducted where the impacts occurred at the "instrumented" end of the test car, that is, the end of the car having the head shield with the strain gauges installed. Each series was then repeated with the test car reversed so that the impacts occurred at the "non-instrumented" end of the test car. Thus a total of six series of tests were conducted.

The first impact of each test series occurred at a minimal "hammer" car speed of 1.8 m/s (4 miles/hour). Subsequent impacts occurred with the minimal speed increased in increments of 0.45 km/s (1 mile/hour) until a coupler force of 5.56 MN (1,250,000 lbs) was reached. The "hammer" car was set into motion by pushing it with a locomotive. When it had reached the desired speed, it was uncoupled from the locomotive and allowed to roll freely toward the "anvil" car. The locomotive was braked so that it did not participate in the impact event.

V. TEST RESULTS AND ANALYSIS

As stated in Section II, only the analysis relevant to the headshield evaluation using the AAR test specifications and procedures is considered in this report. The tests described in Section IV using the second (Figure 8) test condition were conducted in accordance with the AAR .25 test requirement (Appendix C). The impact or "hammer" car used on the tests had a gross weight 15% less than that called for in the AAR specification, but it was the heaviest available. This impact car was a flat car loaded with steel plate to a gross weight of 84.8 Mg (187,000 pounds). The load was securely fastened into place to prevent shifting.

A thorough visual inspection of the test car and its head shield was made after every test. There was no indication of structural damage.

The impact speeds and peak coupler forces are presented in Table II for the test runs associated with the AAR .25 test specification. It should be noted that when the coupler force has reached the threshold of 5.56 MN (1,250,000 pounds), the test was repeated one or more times at the same nominal impact speed. This was done to ensure the acquisition of "worst case" strain data.

The strain gage recordings are characterized by a cyclic waveform where, after the first two or three half-cycles, the absolute value of each succeeding peak diminishes in magnitude. A Fourier analysis of these recordings revealed that the predominant fundamental frequency of the head shield vibrations was

TABLE II. Impact Speed and Coupler Force

Car Orientation	Test No.	Impact Speed m/s	Impact Speed miles/hr.	Coupler Force MN	Coupler Force Pounds
Impact at non-instrumented end	17	2.32	5.2	1.94	435,000
	18	2.68	6.0	4.38	915,000
	19	3.08	6.9	4.95	1,113,000
	20	3.62	8.1	5.70	1,281,000
	21	3.62	8.1	5.85	1,315,000
	22	3.62	8.1	5.80	1,304,000
Impact at instrumented end.	25	2.37	5.3	1.64	369,000
	26	2.73	6.1	3.00	675,000
	27	3.13	7.0	4.30	966,000
	28	3.58	8.0	5.62	1,265,000
	29	3.58	8.0	5.62	1,264,000
	30	3.67	8.2	5.69	1,279,000

16.8 Hz. The first three peaks (that is, the first three half-cycles of vibration) of each record were measured to obtain the magnitude and sign of the strain (tensile strain is positive). Principal strains at each gauge location on the head shield were then calculated using the standard formula for strain gauge rosettes. These strain data are tabulated in Appendix D.

An analysis of the principal strain data revealed that the maximum absolute strains were recorded at strain gauge position number 2, the point on the head shield near its attachment to the center sill connecting bracket. This finding conforms with the predictions made prior to testing. The largest strains occurred on the tests where the coupler force exceeded 5.56 MN (1,250,000 pounds) and where the test car was oriented with its instrumented head shield at the end opposite the impact. Data for nine cases representing the absolute value of the largest measured strains were selected from Appendix D and are summarized in Table III.

The test requirements of AAR .25 specify the conversion of measured strains to stresses using the "idealized true stress-strain curve" of the material involved. The peak stress values thus obtained are not to exceed the yield strength of the material as defined by the 0.2 percent offset method. The head shield under test was constructed of ASTM-A242 steel which has a yield strength of 345 MPa (50,000 psi). A plot of the "idealized true stress-strain curve" is shown in Figure 10. The measured strain values from Table III were entered onto the curve and their corresponding values for peak stress were read and listed in the last column of Table III. It can be seen that in all nine cases the indicated stresses are well below the 345 MPa (50,000) yield strength of the material. Therefore, the head shield design satisfies the requirement set forth in AAR .25.

VI. SUMMARY

The complex response of the tank car head shield resulting from a car-coupling impact warrants that the structural adequacy be examined. This condition is the largest stress that is found in the routine railroad operating environment. The specification set forth in AAR .25 provide a procedure for determining this adequacy, but some questions remain regarding other factors that should be considered in a long term fatigue evaluation. Thus, test conditions other than those of AAR .25 were added to the head shield tests in order to obtain data for this evaluation. The data obtained from these tests showed the currently applicable AAR head shield specification were met; susceptibility to fatigue will be examined in detail and reported in a forthcoming document.

TABLE III. SUMMARY OF STRAIN STRESS DATA

Test No.	Position No.	Head Shield Location	Peak No.	Peak Horiz. Strain	Peak Slant Strain	Peak Vert. Strain	Peak Principal Strain	Peak Stress (from TSS curve) MPa	Peak Stress (from TSS curve) psi
20	2	Left Front	3	+1264	+361	+344	+1443	279	40470
20	2	Right Rear	1	-1514	-790	-502	-1559	-291	-42260
21	2	Left Front	2	-1382	-584	-408	-1473	-283	-41000
21	2	Left Rear	2	+ 503	+515	+1402	+1580	293	42520
21	2	Right Rear	1	-1448	-809	- 595	-1498	-285	-41400
22	2	Left Front	2	-1382	-721	-420	-1415	-276	-40000
22	2	Left Rear	2	+ 521	+598	+1343	+1462	281	40810
22	2	Right Front	1	+1377	+658	+522	+1467	282	40900
22	2	Right Rear	1	-1547	-867	-530	-1575	-293	-42460

NOTE: Values for strain are in μm/m.

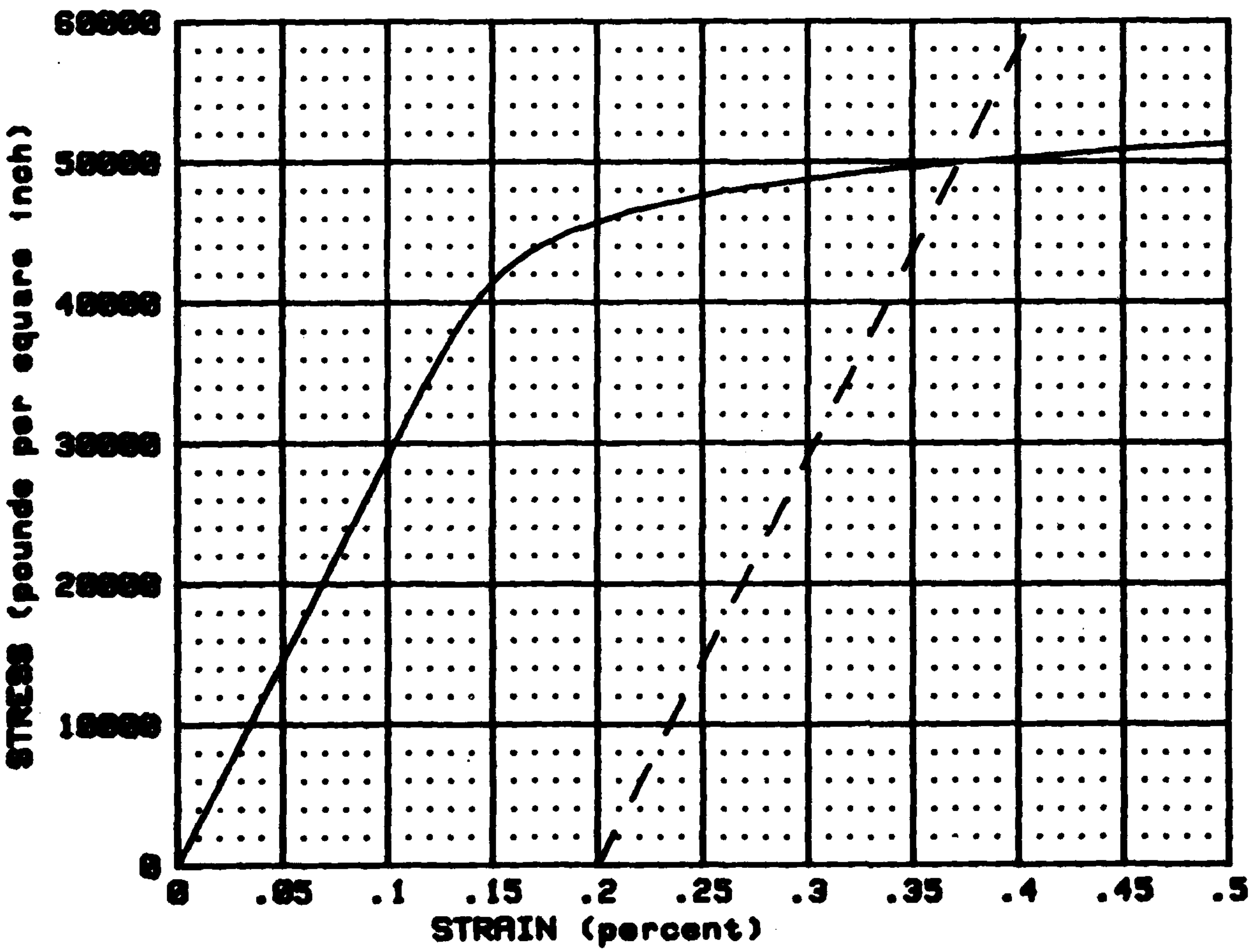


Figure 10. "Idealized True Stress-Strain Curve" for ASTM-A242 Steel

APPENDIX A

CFR 179.100-23 HEAD SHIELDS

(a) After August 30, 1974, each end of a specification DOT-112A and 114A tank car must be equipped with a protective head shield. The shield must be:

(1) At least 1/2-inch thick, and made from steel produced in accordance with specifications ASTM A242, A572-GR50, A515-70, A516-GR70, or AAR TC-128B.

(2) In the shape and size of the lower half of the head of the tank car or in the shape of a trapezoid with the following dimensions:

(i) A minimum width at the top of the center sill of four feet six inches, measured in a straight line between extreme edges;

(ii) A minimum width at the top of shield of nine feet measured in a straight line between the extreme edges. (For cars with diameters less nine feet, the width of the head shield must not extend beyond outermost portion of the head and be not less than three inches from the outermost point of the head.)

(iii) The top corners of the shield rounded to a minimum radius of 9 inches;

(iv) The bottom corners of the shield rounded to a minimum radius of three inches;

(v) All inside edges of the shield chamfered to a minimum of 1/8-inch;

(vi) A minimum height of four feet six inches, and

(vii) Located so that the bottom of the shield touches the top of the center sill.

(3) Shaped to the contour of the tank shell head, utilizing a minimum of three vertical bend lines; and

(4) The head protection device must meet the impact test requirements of paragraph AAR 24-5 in the "Specification for Tank Cars" Standard, effective October 1, 1972. The impact test acceptance criterion is that the device and its supporting structure does not sustain visible permanent damage or deformation such as fracture, cracks, bends, and dents. The object of this requirement is to assure that the head shield has adequate strength to remain attached and functionally unimpaired during normal operations.

(b) The heat protection device must meet all of the workmanship requirements of the "AAR Specifications for Design, Fabrication, and Construction of Freight Cars dated September 1, 1964" (Amendment 179-15, 39 FR 27574, July 30, 1974, as amended by Amendment 179-16, 41 FR 21476, May 26, 1976).

APPENDIX B

AAR.24-5 IMPACT TEST

(a) This test is optional by car builder but mandatory when requested by the Car Construction Committee. An impact test may be performed using a minimum of three cars backing up the test car and four impacting cars, each loaded to a minimum rail load of 177,000 pounds. The brakes must be set on all standing cars after all slack between cars has been eliminated. There must be no precompression of the draft gears. The standing cars must be on level tangent tracks. The striking cars, coupled together, must be used to provide repeated impacts. After each impact, the standing cars must be adjusted if necessary to restore the original condition. A series of impacts must be made at increments of two miles per hour until a coupler force of 1,250,000 pounds has been reached. A visual inspection of the test car must be made during and after each of the tests. Any permanent damage requiring shopping of the car for repairs will be sufficient cause for disapproval of the design. If requested by the Car Construction Committee, strain gauges are to be applied at critical locations and strains recorded during test. Critical locations to be determined by stress coating or other approved method. Coupler forces and impact speeds must be recorded.

(b) The test car must be loaded to at least the rail load limit for the number and size of axles used under the car and must be equipped with the draft gear or cushioning device for which the car was designed. All cars other than test car must be equipped with draft gears meeting the requirements of AAR Specification M-901 and either the struck or striking car must be equipped with an approved means for measuring coupler force. The test car must be impacted by a car of 70 ton nominal capacity, loaded to the allowable gross weight on rails prescribed in 2.1.5.17 of the Design Manual in increments of two miles per hour, until a coupler force of 1,250,000 pounds has been reached. The impacting car should be loaded with a high density material to provide a low center of gravity braced to prevent shifting. A visual inspection of the test car must be made during and after each of the tests. Any permanent damage requiring shopping of the car for repairs will be sufficient cause for disapproval of the design. If requested by the Car Construction Committee, strain gauges are to be applied at critical locations and strains recorded during test. Critical locations to be determined by stress coating or other approved method. Coupler forces and impact speeds must be recorded.

APPENDIX C

AAR.25 DESIGN AND TEST REQUIREMENTS FOR HEAD SHIELD ATTACHMENTS

When head shields are required in accordance with provisions of DOT 179.100-23, the attachment, design calculations and test results must meet the following requirements and be approved by the Tank Car Committee:

(a) Design Conditions

The attachments must be designed so that under the most severe conditions imposed by the following combinations of forces, the calculated stresses will not exceed the minimum yield strength of the material.

Impact Environment

Vertical Combined with Longitudinal

$$F_{vertical} = W_s \left(1 + \frac{7,500,000\ h}{W_c L}\right) \qquad F_{longitudinal} = \frac{1,250,000\ W_s}{W}$$

combined with Lateral

$$F_{lateral} = 1.25\ W_s$$

In-Train Environment

Vertical

$$F_{vertical} = 3\ W_s$$

where

F = Uniformly distributed load acting on head sh

W_s = Weight of head shield including attachments

W = Light-weight of car, pounds

h = Vertical distance between center line of of gravity of empty car, feet

W_c = W less weight of trucks, pounds

L = Length over tank heads, feet

(b) Test Requirements

A qualification impact test must be design of head shield attachments in accord

(1) Head shields with attachments th of the car.

(2) Strain gauges must be applied to both ends of the car at the critical locations. Critical locations to be determined by engineering judgment or stress indicating methods.

(3) The test car, empty, free to roll, must be impacted by a car of 70-ton nominal capacity, loaded to allowable gross weight on rail, in increments of two miles per hour, starting at 6 mph, until a coupler force of 1,250,000 pounds has been reached.

(4) Both ends of the test car must be impacted unless the head shields and attachments are identical at each end.

(5) The measured strains must be converted to stresses using the idealized true stress-strain curves of the material(s) involved. The peak stress may not exceed the yield strength of the material as defined by the 0.2 percent offset method.

(6) A visual inspection of the head shield attachments and head shield must be made during and after each of the tests. Any damage will be sufficient cause for disapproval of the design.

APPENDIX D

MEASURED STRAINS

STRAIN DATA FOR TEST NUMBER 17

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	474	309	166	474	166
Pos. 2, Left front	2	-158	-155	-153	-153	-158
Pos. 2, Left front	3	277	103	115	319	73
Pos. 2, Left rear	1	-162	-299	-435	-162	-435
Pos. 2, Left rear	2	126	192	296	298	124
Pos. 2, Left rear	3	-108	-72	-257	-49	-316
Pos. 2, Right front	1	361	245	179	364	176
Pos. 2, Right front	2	-248	-169	-89	-89	-248
Pos. 2, Right front	3	271	132	119	294	96
Pos. 2, Right rear	1	-395	-270	-186	-184	-397
Pos. 2, Right rear	2	86	231	93	231	-52
Pos. 2, Right rear	3	-189	-116	-112	-99	-202
Pos. 1, Right front	1	-77	-174	-93	4	-174
Pos. 1, Right front	2	86	107	94	107	73
Pos. 1, Right front	3	-189	-187	-146	-138	-197
Pos. 1, Right rear	1	90	187	96	187	-1
Pos. 1, Right rear	2	-113	-83	-64	-63	-114
Pos. 1, Right rear	3	173	146	128	173	128
Pos. 5, Left ctr. sill	1	-112	-150	476	625	-261
Pos. 5, Left ctr. sill	2	127	103	82	127	82
Pos. 5, Left ctr. sill	3	-96	-56	-23	-23	-96
Pos. 5, Right ctr. sill	1	-17	0	-39	2	-58
Pos. 5, Right ctr. sill	2	58	40	65	83	40
Pos. 5, Right ctr. sill	3	-50	-18	-52	-18	-84

NOTE: Values for strain are in μm/m.

STRAIN DATA FOR TEST NUMBER 18

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	750	481	370	766	354
Pos. 2, Left front	2	-553	-361	-280	-269	-564
Pos. 2, Left front	3	632	206	255	747	140
Pos. 2, Left rear	1	-377	-527	-632	-375	-634
Pos. 2, Left rear	2	269	359	592	607	254
Pos. 2, Left rear	3	-233	-215	-573	-150	-656
Pos. 2, Right front	1	722	414	358	761	319
Pos. 2, Right front	2	-587	-414	-224	-224	-587
Pos. 2, Right front	3	677	150	238	835	80
Pos. 2, Right rear	1	-625	-559	-334	-314	-645
Pos. 2, Right rear	2	823	482	242	827	238
Pos. 2, Right rear	3	-560	-212	-251	-158	-653
Pos. 1, Right front	1	-113	-362	-234	24	-371
Pos. 1, Right front	2	172	428	181	428	-75
Pos. 1, Right front	3	-352	-428	-252	-166	-438
Pos. 1, Right rear	1	105	322	231	334	2
Pos. 1, Right rear	2	-248	-385	-141	3	-392
Pos. 1, Right rear	3	331	312	238	339	230
Pos. 5, Left ctr. sill	1	-223	-263	95	191	-319
Pos. 5, Left ctr. sill	2	255	216	-104	303	-152
Pos. 5, Left ctr. sill	3	-239	-160	145	176	-270
Pos. 5, Right ctr. sill	1	-50	49	-74	50	-173
Pos. 5, Right ctr. sill	2	99	-63	157	321	-65
Pos. 5, Right ctr. sill	3	-74	66	-105	67	-246

STRAIN DATA FOR TEST NUMBER 19

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	1224	704	433	1243	414
Pos. 2, Left front	2	-750	-618	-331	-317	-764
Pos. 2, Left front	3	1145	377	318	1276	187
Pos. 2, Left rear	1	-466	-670	-810	-463	-813
Pos. 2, Left rear	2	395	491	948	1002	341
Pos. 2, Left rear	3	-269	-251	-889	-128	-1030
Pos. 2, Right front	1	1219	564	432	1298	353
Pos. 2, Right front	2	-948	-602	-298	-297	-949
Pos. 2, Right front	3	903	282	253	1018	138
Pos. 2, Right rear	1	-1284	-713	-465	-434	-1315
Pos. 2, Right rear	2	1020	751	325	1029	316
Pos. 2, Right rear	3	-1086	-443	-307	-232	-1161
Pos. 1, Right front	1	-215	-589	-345	36	-596
Pos. 1, Right front	2	275	602	345	604	16
Pos. 1, Right front	3	-498	-549	-298	-217	-579
Pos. 1, Right rear	1	188	551	328	559	-43
Pos. 1, Right rear	2	-399	-561	-289	-120	-568
Pos. 1, Right rear	3	459	457	334	483	310
Pos. 5, Left ctr. sill	1	-263	-423	-45	136	-444
Pos. 5, Left ctr. sill	2	327	338	114	379	62
Pos. 5, Left ctr. sill	3	-343	-282	-168	-164	-347
Pos. 5, Right ctr. sill	1	-58	-13	-153	-2	-209
Pos. 5, Right ctr. sill	2	148	44	244	355	37
Pos. 5, Right ctr. sill	3	-91	-88	-140	-79	-152

STRAIN DATA FOR TEST NUMBER 20

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	1382	721	459	1423	418
Pos. 2, Left front	2	-1264	-721	-408	-393	-1279
Pos. 2, Left front	3	1264	361	344	1443	165
Pos. 2, Left rear	1	-592	-814	-1086	-591	-1087
Pos. 2, Left rear	2	377	515	1284	1383	278
Pos. 2, Left rear	3	-287	-335	-1086	-154	-1219
Pos. 2, Right front	1	1264	602	477	1347	394
Pos. 2, Right front	2	-1174	-696	-328	-324	-1178
Pos. 2, Right front	3	1061	301	328	1232	157
Pos. 2, Right rear	1	-1514	-790	-502	-457	-1559
Pos. 2, Right rear	2	1350	848	390	1351	389
Pos. 2, Right rear	3	-1251	-424	-334	-204	-1381
Pos. 1, Right front	1	-309	-750	-351	91	-751
Pos. 1, Right front	2	352	723	410	724	38
Pos. 1, Right front	3	-635	-803	-427	-240	-822
Pos. 1, Right rear	1	301	665	372	667	6
Pos. 1, Right rear	2	-459	-665	-295	-78	-676
Pos. 1, Right rear	3	587	717	321	749	159
Pos. 5, Left ctr. sill	1	-295	-517	-68	173	-536
Pos. 5, Left ctr. sill	2	375	423	159	457	77
Pos. 5, Left ctr. sill	3	-359	-320	-209	-201	-367
Pos. 5, Right ctr. sill	1	-116	71	96	123	-143
Pos. 5, Right ctr. sill	2	165	-124	-210	191	-236
Pos. 5, Right ctr. sill	3	-132	66	244	244	-132

STRAIN DATA FOR TEST NUMBER 21

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	1343	859	535	1351	527
Pos. 2, Left front	2	-1382	-584	-408	-317	-1473
Pos. 2, Left front	3	1304	446	344	1435	213
Pos. 2, Left rear	1	-592	-766	-1027	-588	-1031
Pos. 2, Left rear	2	503	515	1402	1580	325
Pos. 2, Left rear	3	-341	-359	-1086	-199	-1228
Pos. 2, Right front	1	1038	621	552	1094	496
Pos. 2, Right front	2	-1174	-696	-298	-296	-1176
Pos. 2, Right front	3	1174	357	343	1336	181
Pos. 2, Right rear	1	-1448	-809	-595	-545	-1498
Pos. 2, Right rear	2	1382	809	362	1386	358
Pos. 2, Right rear	3	-1284	-501	-381	-272	-1393
Pos. 1, Right front	1	-326	-777	-369	83	-778
Pos. 1, Right front	2	352	736	345	736	-39
Pos. 1, Right front	3	-575	-763	-351	-143	-783
Pos. 1, Right rear	1	301	655	379	657	23
Pos. 1, Right rear	2	-466	-707	-250	7	-723
Pos. 1, Right rear	3	331	655	289	656	-36
Pos. 5, Left ctr. sill	1	-319	-555	-31	231	-581
Pos. 5, Left ctr. sill	2	375	433	136	469	42
Pos. 5, Left ctr. sill	3	-335	-253	-227	-220	-342
Pos. 5, Right ctr. sill	1	-83	-66	-214	-43	-254
Pos. 5, Right ctr. sill	2	157	-110	253	524	-114
Pos. 5, Right ctr. sill	3	-107	31	-179	35	-321

STRAIN DATA FOR TEST NUMBER 22

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT NON-INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	1343	756	471	1368	446
Pos. 2, Left front	2	-1382	-721	-420	-387	-1415
Pos. 2, Left front	3	1027	429	331	1107	251
Pos. 2, Left rear	1	-556	-694	-1007	-540	-1023
Pos. 2, Left rear	2	521	598	1343	1462	402
Pos. 2, Left rear	3	-287	-323	-988	-167	-1108
Pos. 2, Right front	1	1377	658	522	1467	432
Pos. 2, Right front	2	3948	-602	-268	5066	-1386
Pos. 2, Right front	3	767	282	298	876	189
Pos. 2, Right rear	1	-1547	-867	-530	-502	-1575
Pos. 2, Right rear	2	1152	713	446	1162	436
Pos. 2, Right rear	3	-856	-366	-214	-172	-898
Pos. 1, Right front	1	-506	-964	-339	125	-970
Pos. 1, Right front	2	163	576	369	593	-61
Pos. 1, Right front	3	-300	-482	-234	-49	-485
Pos. 1, Right rear	1	369	759	334	759	-56
Pos. 1, Right rear	2	-293	-613	-225	97	-615
Pos. 1, Right rear	3	256	385	270	385	141
Pos. 5, Left ctr. sill	1	-295	-489	-45	173	-513
Pos. 5, Left ctr. sill	2	375	423	45	479	-59
Pos. 5, Left ctr. sill	3	-255	-329	-168	-86	-337
Pos. 5, Right ctr. sill	1	-66	-102	66	121	-121
Pos. 5, Right ctr. sill	2	66	93	-87	118	-139
Pos. 5, Right ctr. sill	3	-116	-106	153	202	-165

STRAIN DATA FOR TEST NUMBER 26

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	-316	0	-185	8	-509
Pos. 2, Left front	2	269	0	198	470	-3
Pos. 2, Left front	3	-221	0	-136	5	-362
Pos. 2, Left rear	1	171	260	380	381	170
Pos. 2, Left rear	2	-181	-190	-234	-176	-239
Pos. 2, Left rear	3	96	80	278	327	47
Pos. 2, Right front	1	-356	-239	-73	-71	-358
Pos. 2, Right front	2	279	203	218	303	194
Pos. 2, Right front	3	-232	-50	-82	-26	-288
Pos. 2, Right rear	1	375	287	150	378	147
Pos. 2, Right rear	2	-254	-215	-150	-148	-256
Pos. 2, Right rear	3	201	108	141	241	101
Pos. 1, Right front	1	102	322	318	366	54
Pos. 1, Right front	2	-146	-177	-102	-67	-181
Pos. 1, Right front	3	124	229	140	229	35
Pos. 1, Right rear	1	-163	-372	-305	-79	-389
Pos. 1, Right rear	2	108	186	153	190	71
Pos. 1, Right rear	3	-157	-232	-139	-64	-232
Pos. 5, Left ctr. sill	1	153	185	75	195	33
Pos. 5, Left ctr. sill	2	-138	-136	-53	-37	-154
Pos. 5, Left ctr. sill	3	100	78	22	104	18
Pos. 5, Right ctr. sill	1	-92	0	105	105	-92
Pos. 5, Right ctr. sill	2	53	0	-171	68	-186
Pos. 5, Right ctr. sill	3	-80	0	77	77	-80

STRAIN DATA FOR TEST NUMBER 27

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	-569	-330	-265	-242	-592
Pos. 2, Left front	2	411	448	265	470	206
Pos. 2, Left front	3	-348	-71	-185	-55	-478
Pos. 2, Left rear	1	363	440	600	607	356
Pos. 2, Left rear	2	-320	-300	-410	-286	-444
Pos. 2, Left rear	3	171	110	366	455	82
Pos. 2, Right front	1	-372	-299	-191	-189	-374
Pos. 2, Right front	2	341	239	281	389	233
Pos. 2, Right front	3	-279	-72	-118	-49	-348
Pos. 2, Right rear	1	335	335	250	353	232
Pos. 2, Right rear	2	-308	-227	-216	-204	-320
Pos. 2, Right rear	3	214	132	183	267	130
Pos. 1, Right front	1	-168	-166	-293	-141	-320
Pos. 1, Right front	2	212	530	370	543	39
Pos. 1, Right front	3	-183	-146	-172	-146	-209
Pos. 1, Right rear	1	-70	130	146	180	-104
Pos. 1, Right rear	2	139	-371	-239	323	-423
Pos. 1, Right rear	3	-198	242	146	292	-344
Pos. 5, Left ctr. sill	1	215	-59	-134	241	-160
Pos. 5, Left ctr. sill	2	-161	283	86	306	-381
Pos. 5, Left ctr. sill	3	130	-185	-81	259	-210
Pos. 5, Right ctr. sill	1	-79	0	-149	5	-233
Pos. 5, Right ctr. sill	2	79	0	132	214	-3
Pos. 5, Right ctr. sill	3	-105	0	44	50	-111

STRAIN DATA FOR TEST NUMBER 28

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	-869	-413	-389	-306	-952
Pos. 2, Left front	2	790	648	463	791	462
Pos. 2, Left front	3	-806	-83	-327	-27	-1106
Pos. 2, Left rear	1	491	480	892	983	400
Pos. 2, Left rear	2	-491	-630	-805	-490	-806
Pos. 2, Left rear	3	246	200	834	989	91
Pos. 2, Right front	1	-635	-610	-272	-214	-693
Pos. 2, Right front	2	682	457	418	711	389
Pos. 2, Right front	3	-589	-180	-245	-124	-710
Pos. 2, Right rear	1	629	467	324	629	324
Pos. 2, Right rear	2	-629	-622	-424	-386	-667
Pos. 2, Right rear	3	469	251	241	509	201
Pos. 1, Right front	1	-227	-478	-350	-89	-488
Pos. 1, Right front	2	358	582	376	582	152
Pos. 1, Right front	3	-432	-333	-236	-236	-432
Pos. 1, Right rear	1	-430	-558	-385	-255	-560
Pos. 1, Right rear	2	424	270	192	430	186
Pos. 1, Right rear	3	-296	-270	-139	-123	-312
Pos. 5, Left ctr. sill	1	-391	-410	91	205	-505
Pos. 5, Left ctr. sill	2	360	205	-150	379	-169
Pos. 5, Left ctr. sill	3	-161	-68	81	84	-164
Pos. 5, Right ctr. sill	1	-145	0	-39	14	-198
Pos. 5, Right ctr. sill	2	158	0	215	375	-2
Pos. 5, Right ctr. sill	3	-105	0	-33	9	-147

STRAIN DATA FOR TEST NUMBER 29

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	-837	-436	-352	-305	-884
Pos. 2, Left front	2	774	590	475	778	471
Pos. 2, Left front	3	-885	-342	-315	-216	-984
Pos. 2, Left rear	1	406	510	804	826	384
Pos. 2, Left rear	2	-470	-580	-819	-458	-831
Pos. 2, Left rear	3	214	220	804	922	96
Pos. 2, Right front	1	-620	-634	-300	-224	-696
Pos. 2, Right front	2	650	443	390	671	369
Pos. 2, Right front	3	-573	-227	-254	-168	-659
Pos. 2, Right rear	1	643	527	316	650	309
Pos. 2, Right rear	2	-629	-527	-432	-432	-629
Pos. 2, Right rear	3	495	239	266	563	198
Pos. 1, Right front	1	88	520	370	552	-94
Pos. 1, Right front	2	-249	-509	-325	-62	-512
Pos. 1, Right front	3	322	540	198	547	-27
Pos. 1, Right rear	1	-157	-437	-372	-61	-468
Pos. 1, Right rear	2	267	446	219	447	39
Pos. 1, Right rear	3	-436	-492	-259	-178	-517
Pos. 5, Left ctr. sill	1	368	419	-129	509	-270
Pos. 5, Left ctr. sill	2	-414	-390	97	186	-503
Pos. 5, Left ctr. sill	3	253	156	-145	278	-170
Pos. 5, Right ctr. sill	1	-171	0	-171	0	-342
Pos. 5, Right ctr. sill	2	79	0	110	190	-1
Pos. 5, Right ctr. sill	3	-145	0	-127	0	-272

STRAIN DATA FOR TEST NUMBER 30

TEST CONFIGURATION: 'ANVIL CAR' TEST (Unrestrained)
IMPACT AT INSTRUMENTED END OF TEST CAR

LOCATION OF STRAIN GAUGE	PEAK NUMBER	HORIZ. STRAIN	SLANT STRAIN	VERTICAL STRAIN	PRINCIPAL STRAIN MAXIMUM	PRINCIPAL STRAIN MINIMUM
Pos. 2, Left front	1	-806	-448	-346	-313	-839
Pos. 2, Left front	2	758	684	650	762	646
Pos. 2, Left front	3	-695	-330	-253	-210	-738
Pos. 2, Left rear	1	406	440	775	829	352
Pos. 2, Left rear	2	-480	-620	-790	-479	-791
Pos. 2, Left rear	3	224	260	658	724	158
Pos. 2, Right front	1	-682	-586	-281	-255	-708
Pos. 2, Right front	2	821	455	418	880	359
Pos. 2, Right front	3	-542	-335	-200	-196	-546
Pos. 2, Right rear	1	669	479	266	669	266
Pos. 2, Right rear	2	-803	-574	-366	-366	-803
Pos. 2, Right rear	3	482	347	166	484	164
Pos. 1, Right front	1	66	395	408	470	4
Pos. 1, Right front	2	-198	-468	-287	-13	-472
Pos. 1, Right front	3	249	499	420	520	149
Pos. 1, Right rear	1	-198	-465	-279	-8	-469
Pos. 1, Right rear	2	174	362	246	366	54
Pos. 1, Right rear	3	-343	-539	-279	-81	-541
Pos. 5, Left ctr. sill	1	360	371	-91	461	-192
Pos. 5, Left ctr. sill	2	-422	-419	81	183	-524
Pos. 5, Left ctr. sill	3	169	185	-97	236	-164
Pos. 5, Right ctr. sill	1	-171	0	160	160	-171
Pos. 5, Right ctr. sill	2	53	0	55	108	0
Pos. 5, Right ctr. sill	3	-132	0	-199	3	-334

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